IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment

Sponsor

Standards Committee
of the
IEEE Electromagnetic Compatibility Society

Approved May 31, 1990

IEEE Standards Board

Abstract: IEEE Std 140-1990, *IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment*, describes procedures that may be applied in the design and construction of radio-frequency heating equipment used for heating in industrial and other purposes, excluding applications in the field of telecommunication and information technology. These procedures are intended to reduce the amount of radio-frequency energy leaks, which can interfere with other equipment and broadcast services; they may also be used as remedial measures when harmful interference occurs.
Keywords: electromagnetic interference, ISM equipment, radio-frequency energy, radio-frequency heating equipment

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ISBN 1-55937-043-2

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Foreword

(This Foreword is not a part of IEEE Std 140-1990, IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment.)

The purpose of this recommended practice is to provide guidance to those responsible for preventing radio-frequency (rf) heating equipment from interfering with other electrical equipment in its environment. RF energy for heating purposes has found multiple applications in industrial, scientific, and medical equipment. Unfortunately, it is virtually impossible to contain all of the rf energy used within rf heating equipment. This recommended practice seeks to give guidance that will prevent interference with other equipment and broadcast services by limiting the amount of rf energy that escapes to low levels.

When it became necessary to review and revise IEEE Std 140-1950 , Jim Maw accepted the chairmanship of the working group and directed the task of updating this standard. The members of the working group contributed their time and energy generously. As this project neared completion, a number of other individuals contributed review and comments, which substantially aided in the completion of the task. These contributors are gratefully acknowledged.

At the time this project was completed, the 140 Working Group consisted of the following members:

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IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment

1. Introduction

The use of radio-frequency (rf) energy for heating in industrial and other processes is essential to manufacturing technology. RF heating equipment is one category of equipment that generates and/or uses rf energy for industrial, scientific, medical, domestic, and other purposes excluding applications in the field of telecommunication and information technology. Equipment so defined is generally called ISM equipment.

It is economically difficult to completely contain the rf energy generated by rf heating equipment. A certain amount of such energy inevitably leaks into the space around the equipment or is conducted over control power wires to other equipment in the vicinity. This radiated and/or conducted rf energy is capable of causing harmful interference to telecommunication services and to information technology equipment and thus is a very important issue. Accordingly, most governments have issued regulations to limit such unintentional radiated and conducted emissions.

The procedures described should be applied in equipment design and construction. The user should carefully follow the manufacturer's recommendations and keep the specified structure complete and in good condition. These procedures may be used as remedial measures when harmful interference occurs. It is much less expensive, however, to incorporate EMC techniques in the original design than to correct errors after installation.

2. References

This recommended practice shall be used in conjunction with the following publications. A bibliography is included in Section 7 for further information.

[1] ANSI C63.2-1987, American National Standard for Instrumentation—Electromagnetic Noise and Field Strength, 10 kHz to 40 GHz — Specifications.[1]

[2] ANSI C63.4-1988, American National Standard Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz.

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[1] ANSI publications can be obtained from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[3] ANSI C95.1-1982, American National Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 300 kHz to 100 GHz.[2]

[4] ANSI/NPFA 70-1990, National Electrical Code, 1990 ed.[3]

[5] IEEE Std 100-1988, IEEE Standard Dictionary of Electrical and Electronics Terms — 4th ed. (ANSI).[4]

[6] IEEE Std 139-1988, IEEE Recommended Practice for Measurement of Radio Frequency Emission from Industrial, Scientific, and Medical (ISM) Equipment Installed on User's Premises (ANSI).

[7] IEEE Std 473-1985, IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz) (ANSI).

[8] IEEE Std 518-1982, IEEE Guide for the Installation of Electrical Equipment to Minimize Noise Inputs to Controllers from External Sources (ANSI).

[9] US Federal Communications Commission, Title 47, Code of Federal Regulations, pt. 2 — Frequency Allocations and Radio Treaty Matters; General Rules and Regulations.[5]

[10] US Federal Communications Commission, Title 47, Code of Federal Regulations, pt. 18 — Industrial, Scientific and Medical Service.

3. Definitions

Unless otherwise noted, all technical definitions are in accordance with those given in IEEE Std 100-1988 [5].[6]

Poulsen arc (also Poulsen singing arc or singing arc): A type of arc-gap transmitting circuit that uses a resistance-capacitance (rc) circuit to tune the arc. This technique substantially reduces the bandwidth used by the arc-gap transmitter.

4. General

4.1 The Need for Shielding

4.1.1 Local Effects

The electrical behavior of high-frequency power gives the impression that it does not follow electrical laws applicable at lower frequencies, where power capability is typically measured in kilowatts and radiation allowance is only a few milliwatts. Actually, there is no fundamental difference. The difficulty lies only in the fact that effects that were negligible at 60 Hz become very important as the frequency is raised. It becomes increasingly difficult to confine electric currents to desired circuits. Dangerous potentials may exist between apparatus cases that can cause burns to operators as well as serious radiation emissions. High-frequency currents may circulate in control devices and make them inoperative or otherwise impair their functions. Circuits and structures that are not associated with the equipment

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[2] ANSI C95.1-1982 has been withdrawn. Copies can be obtained from ANSI.

[3] NFPA publications are available from Publications Sales, National Fire Protection Association, Batterymarch Park, Quincy, MA 02269 or from ANSI.

[4] IEEE publications can be obtained from the Service Center, The Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331 or from ANSI.

[5] For sale by the Superintendent of Documents, US Government Printing Office, Washington, DC, 20554.

[6] The numbers in brackets correspond to those of the references listed in Section 2. When preceded by B, they correspond to the bibliography in Section 7..

in any way may pick up high-frequency currents. The solution to all such hazards is the use of shielding and filtering to confine the currents to safe channels.

4.1.2 Remote Effects

High-frequency energy can propagate through free space and through wires, causing interference to equipment at great distances from the source. The energy may travel along the earth's surface or be conducted on wires directly to the remote point, or it may be reflected from the ionosphere to be returned to earth at tremendous distances from its source. Again, the solution lies in adequate shielding and design of the high-frequency circuits. Surprisingly small amounts of radiated power can cause considerable trouble of this nature.

There are always high-frequency currents inside a cabinet. They must be kept inside and not allowed to escape. A poor joint (one that is dirty, loose, etc.) or an opening are places from which currents may escape, so they must be eliminated.

Good shielding includes the following:

1) A high-conductivity enclosure
2) Good, clean contact between cabinet parts
3) Minimum openings
4) Shielded openings
5) Waveguides where needed
6) Use of interlocks
7) Filtering of electrical conductors where they penetrate the shield

Shielding integrity is dependent on regular maintenance.

As operating frequencies increase, coupling effects, which are negligible at 60 Hz, become significant. Dangerous potentials may develop between nearby exposed conductors. High-frequency voltage may be induced in control devices, making them inoperative. Electromagnetic fields radiated by the equipment may interfere with other, independent devices, as well as licensed radio communications and navigation systems. To prevent these dangers, adequate shielding, filtering, and grounding are essential.

4.2 Nature of Radiation

4.2.1 Types of Generator Equipment

The oldest type of generating equipment is the rotating machine. However, this device is not generally used above 10 kH. In the range of 10 to 500 kH, common power sources were the spark gap and Poulsen arc. Interference from spark equipment is distributed over a very wide frequency range. For example, a 20 kH generator will radiate a continuous spectrum of noise that is very similar to automobile ignition interference, which may extend well into the very-high-frequency regions.

Even if the operating frequency of the ISM equipment will not cause interference, harmonics can be generated by nonlinear elements in the system, and parasitic oscillations may be generated on nonharmonically related frequencies.

Nonlinear electrical components distort waves, generating frequencies that are harmonics, as well as sideband frequencies that bear no harmonic relation to the fundamental. In addition, such phenomena as moding and parasitic oscillations cause trouble. Moding is a sudden frequency shift or “skip” of the generator during the loading procedure. It is a normal tank circuit characteristic that is present when a tuned load is tightly coupled to the tank. Parasitic oscillations are spurious frequencies generated by a feedback path other than the normal path, resulting in unwanted oscillations in the generator.

4.2.2 Sources of Emission

Currents along the edge and over the outside surfaces of conductive enclosures surrounding the apparatus are serious sources of emissions. For example, in Fig 1, the need for shielding was recognized by the designer, but the shielding is inadequate. At the applicator, the shielding is large-mesh iron screen with a high surface reactance and a high loss due to the resistance of the iron. This produces excessive penetration of the circulating currents from the inside face of the screen to the outside face, and results in currents I_1 and I_2. A large opening for the conveyor belt gives rise to currents I_3 around the periphery of the opening. The thickness and conductivity of the generator shield are adequate, but poor contact around the door causes current I_6. Similarly, a slit in the side panel results in an external current I_7. Some additional leaks might be poorly screened windows, open floors, and poor joints around panels.

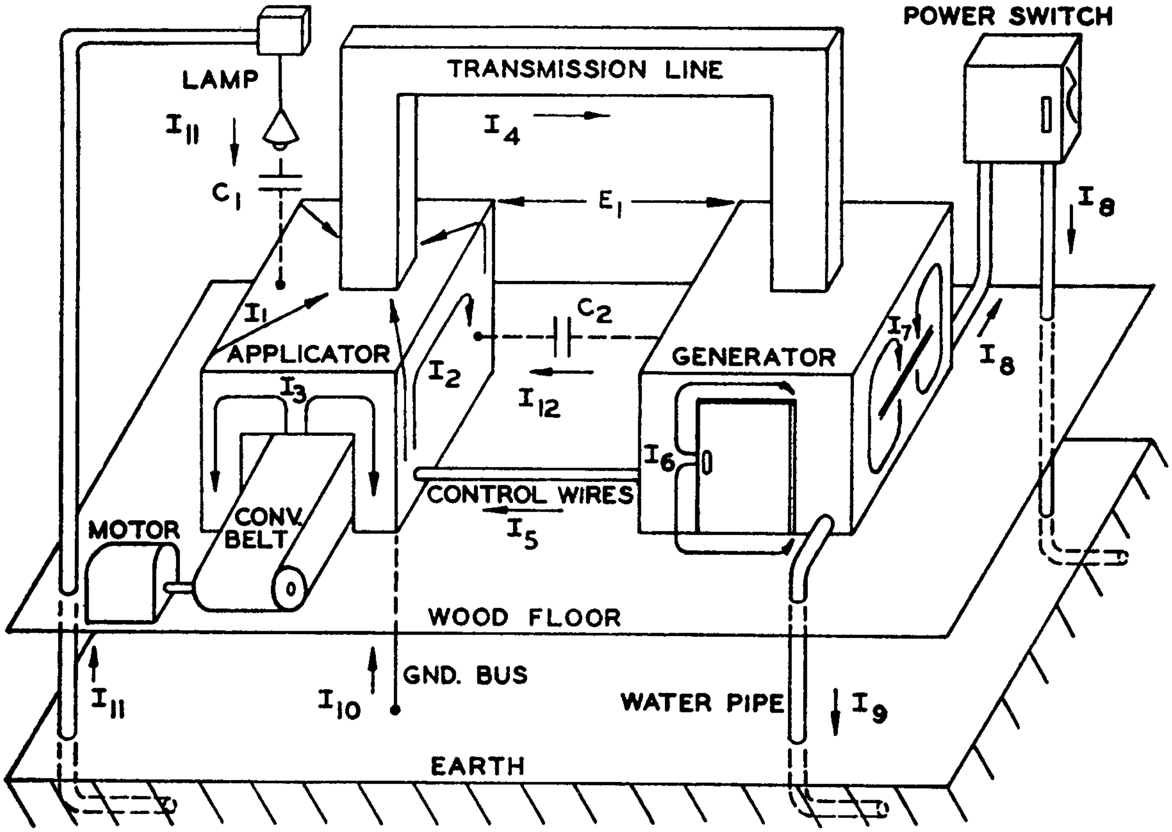


Figure 1—Examples of Typical Emission Sources

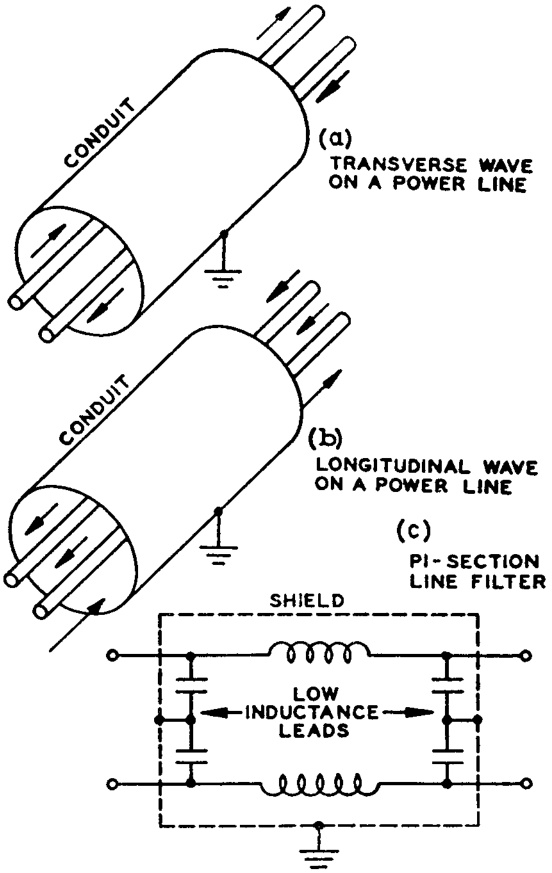


Figure 2—Current Propagation Modes and Pi-Filtering Technique

Current on power and control wires occurs in two ways. Figure 2(a) shows a transverse (wire-to-wire) current mode. Figure 2(b) shows a longitudinal (wire-to-ground) mode. Both modes are transmitted on the inside of a shielding conduit from the installation to a point where the wires may be exposed to free space and cause radiation. The emission per ampere is apt to be much greater for longitudinal current than for transverse current. On the other hand, currents such as I_4, I_5, I_8, I_9, and I_{11} (Fig 1) may be induced on the outside of power conduits due to shielding leaks. A similar current I_9 can occur on the outside of pipes connected to the unit for supplying water, gas, or air to the installation. Isolate the heating equipment if possible. Current I_3 could be reduced by using a waveguide below cutoff at the applicator entrance. Currents I_8, I_9, and I_{11} can be minimized by isolation of the electrical conduit and water pipes.

A common fallacy is the belief that connecting the apparatus to ground is a convenient cure for high-frequency troubles. Some installers have gone to great pains only to discover that no improvement has been obtained. Such a connection with current I_{10} is shown. It usually has considerable radiation resistance and may actually *increase* interference instead of reducing it.

Finally, care must also be exercised to ensure the integrity of the shielding and bonding after construction changes take place in the room in which the equipment is housed. A notable source of trouble is when a hole is cut in a screened wall to insert a pipe and the hole is not sealed after the work is completed. Even without such changes, an installation that initially may have been satisfactory eventually may start to leak high-frequency power. Factors contributing to this condition are corrosion of metal parts and carelessness on the part of the operators, or modification to the existing equipment. A poor choice of metals from an electrochemical standpoint may weaken a joint or contact in time due to corrosion.

4.2.3 Equipment Potentials

The various paths in Fig 1 may be reduced to simple electric circuits. Voltages are induced across the equivalent impedance by direct conduction, by capacity coupling (for example, stray capacities C_1 and C_2), by inductive coupling, or by direct radiation. One such voltage is E_1 between the generator and applicator, due to the impedance of various current paths between them. Voltages are present even if one cannot calculate the impedance.

In the case of spark generators, the complex form of such interference may shock-excite a number of paths at their resonant frequencies. This may result in radiation peaks at certain frequencies that are higher than the general level of interference. SCRs in induction-heating equipment can produce a similar type of interference. Not all equipment will.

4.2.4 The Electromagnetic Interference Field in Space

Once the high-frequency energy is radiated, it continues to propagate outward in all directions. In this medium, the “wave concept” is useful. All electromagnetic fields have two components, an H (magnetic) and an E (electric) field component. In a free-space radiated field each is composed of only components transverse to the direction of propagation. The associated wave impedance is equal to $-120^{\pi}\ \Omega$. The propagating mode of the radiated field may be further divided into ground- and sky-wave components. Any ground wave may consist of three components: (1) direct line-of-sight wave, (2) ground reflected wave, and (3) a surface wave coupled in and propagating along the ground-air interface. The sky-wave mode may be either reflected or refracted by the ionosphere. The ground wave is affected by the conductivity, dielectric permittivity, and magnetic permeability of the earth and may attenuate rapidly over land. Sky-wave attenuation varies in a complicated manner with frequency, location, and time of day.

The abundance of radiation sources in Fig 1 are found to have different relative phases at the various points in space, varying in such a way that at certain points they tend to add and at other nearby points they tend to subtract. Reflections from metallic objects or electrical discontinuities in the neighborhood will produce secondary waves that give rise to pronounced “interference patterns” or “standing wave patterns.”

4.2.5 Effect of Frequency

The ability of a conductor to radiate energy from its surface increases with increasing frequency. This is due entirely to its increasing electrical length (length in terms of the ratio of circuit dimensions to the wavelength of the current it carries), and its increasing electrical spacing from a ground or other reflecting plane. At frequencies used for induction heating (60 kHz to 450 kHz), electrical lengths are short. If only the induction heating frequencies had to be contended with, the designer could use simple shielding techniques. Unfortunately, harmonic frequencies and parasitic oscillations require the incorporation of high-frequency shielding techniques.

At lower frequencies the conduction of currents along power lines is a considerable source of interference at a distance from the equipment.

4.3 Location and Measurement of Radiation

4.3.1 Field-Strength Meters

Field-strength meters are calibrated receivers. Below 18 MHz, a loop antenna is employed. Between 18 and 30 MHz either the loop or dipole may be used. Above 30 MHz, the specified antenna is a half-wave dipole, mounted on an appropriate support. Data taken with such meters at close spacings (within 1/6 wavelength) should recognize the possible presence of a strong magnetic field.

4.3.2 Other Instruments

For such a purpose as identifying the frequencies of interfering sources, locating leaks in shields, and so forth, various instruments may be useful. Such instruments include interference locators, radio-noise meters with rod antenna or loop probe, and others. Isotropic antennas and broadband field-strength meters can be purchased from various manufacturers.

The Occupational Safety and Health Administration (OSHA) specifies use of meters meeting the standards set forth in ANSI C95.1-1982 [3]. Exposure limits vary with frequency.

4.3.3 Operating Conditions for Tests

It is necessary that all radiation tests be made with the equipment tuned and the applicator and generator voltages in the normal operating range.

4.3.4 Ambient Noise Levels

The weakest field that may be explored with a field-strength meter is determined by the ambient noise level in the vicinity of the meter. Such noise tends to mask the signal and cause erroneous readings.

4.3.5 Conducted Interference

Stray energy may also travel along metallic paths (wires, etc.) to a remote point where it may cause interference with the operation of other apparatus. This is known as conducted interference.

4.3.6 Polarization

The rate at which a ground wave attenuates depends largely upon its polarization in space. The earth acts as a “lossy” dielectric, which is alternately charged and discharged by the advancing wave energy. The net effect is attenuation of the ground wave, which is very high for horizontal polarization (electric vector horizontal), but less for vertical polarization.

4.4 Remedial Methods

4.4.1 Physical Separation

The field strength of an electromagnetic wave varies with distance D^{-1} from the source, as D^{-1} to D^{-3}. Hence, physical isolation from any receiving point is one method of attenuation. In most cases, it is not practical.

4.4.2 Reduction of Bandwidth

An example would be the installation of “snubbers” using SCRs and SS rectifiers. Another example would be the substitution of a filtered dc supply in self-rectified tube generators. Also, one could use signal-line filtering and shaping pulses to reduce their rates of rise and fall.

4.4.3 Cancellations

This suppression method cancels one field with another of equal amplitude and opposite phase. Cancellation occurs when a current-carrying conductor is brought close to a parallel reflecting surface. Similarly, when a conductor carrying an equal and opposite return current is brought close to the transmitting conductor, partial cancellation takes place. Open-wire transmission lines and twisted-pair signal lines use this principle. As another example, the balanced operation of a tuned circuit may, in some instances, reduce the effect on other circuits by cancellation of the induced fields.

4.4.4 Shielding

An effective shield is made of a good conductor completely surrounding the radiation sources. The lower the surface resistance of such a shield, the more efficient it becomes.

Single shields often produce sufficient attenuation. A second shield surrounding the first, and insulated from it, gives approximately twice the attenuation (in decibels) of single shield. When the shields are placed to form an inner and outer shield and are then shorted together (such as in cell-type construction), the attenuation is somewhat reduced but still higher than for a single shield.

Attenuation is impaired by slits, poor joints, the use of high-resistance materials, too large a mesh screen, poor conduction between mesh wires, undue proximity of internal circuits, or unscreened openings.

As pointed out previously, an attempt is often made to use the earth as an equipotential plane connecting each piece of apparatus to a good earth ground (multiple grounding). At best, this yields only mediocre results and may exacerbate the problem since in practice, it is generally impossible to place apparatus cases at true ground potential because of positive ground-wire and shield impedance.

4.4.5 Absorption

A considerable amount of attenuation may be introduced by surrounding an interference source with an absorbing material. Iron and steel, with their high resistance, are fairly effective for this purpose. A laminated shield consisting of sheet steel with a thick copper plating impedes the progress of a radio wave in two ways: (1) The copper surface reflects electric energy; (2) The steel core absorbs energy that penetrates the copper barrier. Ferrite beads may be slipped around power conductors to absorb the radio-frequency energy in these conductors.

5. Good Engineering Practice

5.1 Design of Equipment

5.1.1 Choice of Frequency

Table 1 lists frequencies assigned by international agreement for use of ISM equipment. Emissions on these frequencies are generally not required to be limited. The international agreement provides that communication equipment operating on an ISM frequency shall accept any interference that it may receive from ISM equipment.

If at all feasible, it is highly desirable to operate rf heating equipment on one of the ISM frequencies. However, operating on an ISM frequency is no cure-all for interference, since emissions on harmonic and parasitic frequencies must be considered.

NOTE — The use of 6.78 MHz shall be subject to special authorization by the administration concerned, in agreement with other administrations whose radio communication services might be affected (see [9]). In applying this provision, administrations shall have due regard to the latest relevant CCIR (International Radio Consultative Committee of the International Telecommunications Union) Recommendations.

Among the frequencies to be avoided are those assigned to distress, navigation, and domestic broadcast and television. The possibility of harmonics, sidebands, or broadband noise occurring in these bands should be considered. Many kinds of heating are most efficient at frequencies that fall in some of these bands. In these cases, extraordinary care in shielding and filtering are required.

Table 1—Frequencies Assigned for ISM Equipment

ISM Frequency	Tolerance
6.78 MHz	± 15.0 kHz
13.56 MHz	± 7.0 kHz
27.12 MHz	± 163.0 kHz
40.68 MHz	±20.0 kHz
915.00 MHz	± 13.0 MHz
2 450.00 MHz	± 50.0 MHz
5 800.00 MHz	± 75.0 MHz
24.125 GHz	± 125.0 MHz
61.250 GHz	± 250.0 MHz
122.500 GHz	±500.0 MHz
245.000 GHz	± 1.0 GHz

5.1.2 Suppression of Spurious Frequencies

Well-known engineering practice should be followed to avoid harmonics, parasitic oscillations, and moding. The waveform of the generated frequency should be as undistorted as is consistent with economical design.

5.1.3 Shielding

The rf generator should be housed in an effective shield. Louvers, windows, or other openings must be screened; if in the rf section, the edges of such screening shall be securely bonded to the main shield. Plating to improve the conductivity of shielding and improve the corrosion resistance of joints is advisable. Sufficient thickness of metal should be used to avoid current penetration. Contacting surfaces should be free of paint, dirt, or corrosion. Doors should be continuously bonded to the main shield around their entire periphery by contacting fingers or other suitable means. Door interlocks should be incorporated to prevent operation when opened for both personal safety and emission reduction.

It is good practice to protect internal components not associated with the generating circuits from high-frequency currents. This applies to control wires, meters, relays, low-frequency and dc supply circuits, etc. Shielding and filtering of the generator is often simplified by the use of a separate internal shield, surrounding the high-frequency circuits only.

Where generators require transmission lines, they should be designed for use with coaxial line. Other types of lines are a (1) single shielded pair, (2) two-wire individually shielded pair, and (3) two-wire open line. In cases where the work circuit must be unshielded (some induction heating installations) the circuit should be as compact as possible and located close to the generator. The use of open-wire feed lines should be avoided; if they are used, they should be as short as possible and closely spaced. If possible, they should be balanced to ground and run as near a ground plane as possible. When practicable, the work area should be enclosed in a screened booth.

5.1.4 Power-Line Filter

A power-line filter should be incorporated in the generator. The use of unshielded auxiliary circuits should be avoided; if they are used, they should be effectively filtered.

Nodal (reflection) points in wire conductors may be obtained by line filters or shielded transformers. Figure 2(c) shows a low-pass pi-section filter, which is effective against the transmission of both longitudinal and current transverse current modes. It is desirable to choose the image impedance of such a filter that is as low as possible. The cutoff frequency should be well below the lowest frequency present in the generator output. Low-loss conductors should be used. Additional precautions to ensure high attenuation at fundamental and harmonic frequencies include low capacitor inductance, low ground-wire impedance, low capacitance between input and output terminals, shielded assembly, and mounting of the filter shield directly on the wall of the main apparatus shield at the point where the filtered wires (feed-through filters) leave the main shield. Such line filters are generally used to block high-frequency energy in wire circuits that, without filters, could reach open space. In place of a line filter, it is often possible to insert an isolation transformer with a grounded (electrostatic) shield between primary and secondary, in series with a wire circuit. The ground return from this shield must have negligible impedance. Those transformers are usually good at low frequencies (less than 1 MHz), while filters may be obtained to attenuate high frequencies (from 14 kHz to 1000 MHz).

5.1.5 Plumbing, Grounding, and Conduits

All metal pipes associated with power supplies, grounding, and similar connections should enter the installation at a single point. Water cooling pipes should be isolated from the equipment with a section of plastic pipe. If the power line is properly filtered, the conduit should also be isolated with plastic pipe. (See ANSI/NFPA 70-1990 [4], Art. 331-1 through 331-4.) If this is not done, potentials across the shield surfaces, due to various small leaks, will cause currents such as I_8, I_9, and I_{10} to flow (see Fig 1). Such piping should be bonded to the shielding using wide-short conductors at the point of entry. With these bonds, high-frequency currents will be effectively short-circuited and will not be conducted from the inside to the outside of the shield. Preferably such connections should approach from underground.

5.1.6 Performance Tests

Before a design is released for production, one of the tests should be a thorough check for high-frequency leakage with a sensitive probe, a leak detector, or equivalent. Such tests should be made over as wide a frequency range as possible, in order to locate harmonic or other spurious frequency radiation.

If possible, the life expectancy and reliability of shielding devices should be checked.

If appreciable radiation or poor design is discovered by such tests, every effort should be made at improvement. This will lessen effort required in interference reduction for every installation.

5.2 Installation

5.2.1 Location

A preferred location for high-frequency equipment is on the first floor or in the basement of a building. The equipment should be as remote as possible from metallic ducts and flues, steam pipes, power circuits, or any electrical wiring that may pick up energy by capacitive or inductive coupling. It is very desirable to have the entire equipment housed in a shielded room, although this is not always practical. In any case, the installation should be as compact as possible, with emphasis on short, direct connections between units. Placing components of an installation on a large metal sheet may be helpful.

5.2.2 The Transmission Line

The transmission line should be of the concentric, shielded duct type, or coaxial types. The outer conductor may be fabricated of solid copper, copper-plated steel, or aluminum. It is essential that the outer conductor be continuous, for example, where two sections of fabricated sheet metal outer conductor are bolted together. Such joints and access covers shall be fastened with screws, spaced not more than 10 cm apart.

Large, radiating loop circuits may be avoided by running the line between units along the metal base of the installation. The spacing between the inner conductor and the outer shield shall be consistent to provide a uniform characteristic impedance.

5.2.3 The Applicator

If the generator has been properly designed, the major source of interference will be the applicator, because of the difficulty of containing the *E* and *H* fields, and currents associated with the work piece. Therefore, extreme care must be taken in its shielding.

The applicator shield may be fabricated from copper, copper-plated steel, aluminum, or copper or bronze screening. If screening is used, it should meet the minimum requirements of 16 × 16 mesh, 0.018 wire diameter (0.457 mm). It is best to use expanded or perforated metal.

If the latter is used, a double-wall shield will give better results than a single-wall shield. However, adequate shielding can frequently be attained with a single-wall shield at a lower cost if proper attention is paid to the details of construction. Shield currents can usually be greatly reduced by an internal partial shield. This appears to be particularly useful where the electrodes are large and stray capacitances set up high shield currents. Tuned circuits utilized inside the shield should be attached to it at only a single point, to avoid circulating tank currents in the walls.

The applicator, wherever physically possible, must be completely enclosed by the shield with no openings or discontinuities in the bonding. Paint must be removed at all surfaces of contact. These surfaces should be inspected at monthly intervals and any corrosion removed. Joints in the metal shield material may be made as in Fig 3. Typical door construction is shown in Fig 4, with continuous bonding around the entire periphery. The spring-like bonding strips are of berylium-copper or phosphor-bronze construction. Brass or bronze weather stripping, resilient metal mesh, or perforated sheet metal may be substituted for the construction shown. The shield should be as large as space and cost will permit. Under no conditions should the electrodes be spaced less than 30 cm from any part of the shield. This would be adequate for powers in excess of 5 kW (output) and proportionately less for lower powers. For the megahertz range of industrial heating, generous overlap of metal sheeting is helpful in cases where hooked joints, or closely spaced fasteners, are impractical.

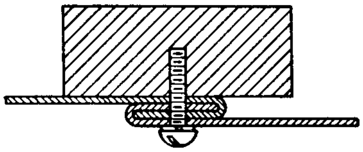


Figure 3—A Suggested Method for Maintaining Contact at Shield Joints

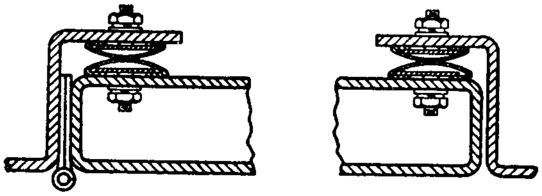


Figure 4—A Suggested Method for Door Bonding

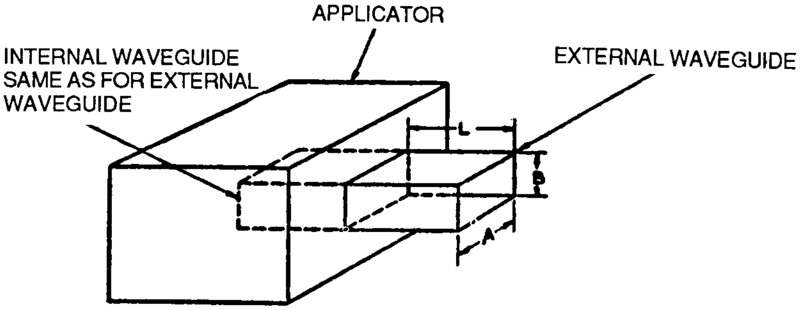
In some installations, mainly conveyor belt operations, it becomes essential that openings be provided. In these cases, it is necessary to construct waveguides below cutoff as shown in Fig 5. Waveguides below cutoff have an attenuation that is a function of *L*, *A*, and *B* and the frequencies to be attenuated. For further information, consult [B8]. With a rectangular cross-section, as shown, $L = A$ or$B$ if the electric field is not across the opening (such as in a stray field arrangement). Otherwise, $L = 2A$ or $2B$ for normal parallel plate electrodes 30 cm from the interior wall. Also, the voltage on the electrode is a factor — high voltage needs longer waveguides.

The waveguides should be as narrow as possible to keep cutoff frequency as high as possible. If harmonics are greater than cutoff, they will pass through the waveguide unimpeded. Furthermore, the larger of the dimensions A and B should exceed approximately one-third the free-space wavelength of highest frequency to be suppressed. Such waveguides should not be located in wall surfaces carrying high currents, or in close proximity to a strong electric field.

Shielding of the applicator floor should not be overlooked. It is important that it be a continuous part of the whole shield, running underneath all of the enclosed components, and securely bonded to all sides and ends.

5.2.4 Wiring

Control wiring must be kept out of the applicator wherever possible. If internal wiring becomes necessary, as large a proportion of the circuit as possible should be run externally and shielded with metal conduit. Conduit should be terminated at both ends in a metal enclosure, such as a junction box or other shield fitting. Unfiltered wires should not be extended into the open. It is recommended that the main power supply to the equipment pass through a line filter before leaving a conduit. Also, the conduit should be isolated, i.e., by inserting a nonconductive section into the conduit forming the isolation. (I_8 in Fig 1 could be eliminated.) This applies also to auxiliary power lines that may bypass the main filter.



NOTE — Shielding characeristics of the internal or external waveguides are the same. Selection of either for a specific application is based mainly on physical considerations.

Figure 5—Applicator Shielding Waveguides

The use of tinned, stranded braid is to be preferred to spirally-wrapped metal sheathing (armored cable[7]), due to eventual corrosion and poor contact between turns, which will result in high-frequency leakage. However, a solid shield is best.

5.2.5 System Ground

If the system is properly shielded, there is no necessity for grounding, other than for safety. For this purpose, a standard underwriter's safety ground may be installed, or the conduit return to the main entrance switch may be used as a 60 Hz or dc ground.

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[7] Formerly called BX cable

5.2.6 Performance Tests

Information pertaining to these measurement procedures may be found in IEEE Std 139-1988 [6]. If the tests show the need for improving shielding, the location of trouble sources is greatly facilitated by a current probe such as previously described. Methods of suppression as described in this recommended practice should be followed. It is again pointed out that prevention by proper design is a much better policy than extended series of cures after the installation is complete.

5.3 Use and Maintenance

5.3.1 Operation

The equipment should always be operated within its power, electrode voltages, and frequency ratings. Access panels, doors and shields, and fasteners should always be in place when the unit is operating. Installers' or manufacturers' instructions should be observed. Warning notices to this effect shall be posted near the equipment. Fasteners are needed to avoid radiation interference, not just to hold the panels in place. Use all of them and keep them tight.

5.3.2 Changes

Any changes in operation, i.e., increase in power output, change in length of extended electrode, or repairs and modifications, should be made in accordance with good engineering practices as described in this recommended practice.

5.3.3 Maintenance

A regular maintenance schedule should be followed to ensure the proper operations of shielding devices. All contacts and bonding strips used in conjunction with openings should be cleaned whenever they show evidence of corrosion. Atmospheres corrosive to copper, bronze, aluminum, etc., are often prevalent in factories, and may quickly reduce the efficiency of a shield by attacking bonding surfaces. Latches, screws, or other devices fastening these surfaces should be tightened periodically.

Such precautions may be incorporated as part of the regular maintenance schedule for the equipment.

6. Procedures to Be Used When Interference Is Encountered

6.1 General

6.1.1 Interference With a Radio Service

Even though the field strength from an installation may comply with regulatory limitations, it is still possible that interference may occur with nearby communication services under abnormal circumstances. Such interference shall be eliminated promptly.

6.1.2 Excessive Radiation

Faulty shielding, poor design, and other factors often cause leakage currents and excessive radiation from an installation after it is completed. Reduction of the radiation to at least specified limits is necessary.

6.1.3 Modernization of Equipment

Equipment existing prior to the adoption of any rules and regulations that does not comply with present laws shall be modified. In the meantime, if such equipment is found to interfere with any authorized radio service, steps to eliminate the interference shall be taken.

6.2 Preliminary Checks

6.2.1 Listening Tests

Where interference or excessive radiation is reported and a field-intensity meter is not readily available, it is often possible to temporarily obtain an rf receiver of proper frequency range that can give an indication of the field (in comparison with other signals) and the nature of transmission causing the interference. The following assessments are recommended:

1) Does the interfering signal have the same frequency as, or bear a harmonic relationship with, the suspected generator frequency?
2) Does the interfering signal fade? This may indicate either a location remote from the receiving point, or that the origin of the signal is a moving source. Ifit is always present, it may suggest a local signal or stationary source.
3) Does the interfering signal have a characteristic tone, or a noise that is identifiable with the suspected source?
4) Does the interfering signal have a temporal pattern that is identifiable with the suspected source?

It is often possible to arrange an identifiable schedule of operation for the suspected generator, such as “2 minutes ON — 30 seconds OFF” during a known test period.

6.2.2 Measurement of Interference

To perform a very approximate check on the interference level, and to observe the effect of any steps taken as corrective, it is possible to use the “S meter” on a communications receiver. Roughly, such a meter is calibrated in steps of 6 dB between successive S points, with a signal of 50 to 100 μV at the receiver terminals, corresponding to S9. This method should be used only as a temporary expedient. Calibration varies between manufacturers, and there is no way of correcting for the antenna length, current distribution, directional characteristics, impedance mismatching, and height above ground, or the variation of receiver gain with frequency. These factors must be known in order to calculate the actual field strength.

A more accurate method of making field-strength observations or noise measurements is with a field-intensity (FI) or noise meter. The various factors affecting calibration have been carefully evaluated for FI meters, so that readings indicate the true intensity of the field arriving at the surface of the antenna. When the FI meters are properly designed and used, and their readings are properly interpreted, they give results that are nationally and internationally accepted; see IEEE Std 139-1988 [6], and IEEE Std 473-1985 [7].

6.3 Location of Sources

6.3.1 Identifying a Faulty Installation

Having ascertained that interference or excessive radiation exists, the first step is to determine which unit is at fault, if several are suspected. Careful observation of frequency, operating sequence, or other characteristics may quickly solve this problem. These techniques may be supplemented through the use of direction-finding loop or other directional antennas, such as are frequently incorporated on field-strength meters. Loops are most accurately utilized by rotating them until a minimum reading is obtained. The direction from which the radiation is coming is then perpendicular to the plane of the loop (assuming the loop is in the far-field zone). By taking a directional reading at each of two known points, the interference source may be determined by triangulation. Loop direction finders are subject to a 180° error because two minima appear as they are rotated through 360°. They also may be inaccurate because of reflections from nearby conductors or other reflecting media.

Dipole antennas may be similarly used to indicate direction of the source, but they are extremely subject to ground, polarization, and reflection errors.

Another search procedure is by a process of “homing” with a portable receiver. The radiating generator is “tracked down” by following along the direction in which the signal increases. This method is again handicapped to some extent by reflection.

6.3.2 Locating High-Frequency Current Leaks

Once the installation causing the interference has been spotted, the problem of reducing leakage is greatly simplified by locating faults in shielding with a current probe, as previously suggested. Leakage currents induce voltages in the pickup loop by mutual induction. The entire unit is shielded in order to minimize body capacitance effects. A probe has directional characteristics that are useful in plotting the main current paths, illustrated in Fig 1. This feature is best utilized by turning the loop for a minimum reading of the meter. The path of the stray current will then be perpendicular to the plane of the loop (assuming the loop is in the near-field zone).

When available, noise meters and interference locators may be used for locating shield faults. More accurate, quantitative data is obtainable in this way, but it will often be found that the simple probe as described is entirely adequate.

6.4 Corrective Measures

6.4.1 Frequency Shift

Where the radiation is within acceptable limitations, the interference to a service may sometimes be quickly eliminated by merely changing the frequency sufficiently to avoid any possibility of operation in the service channel.

6.4.2 Automatic Frequency Control

In some instances, it may be possible to place the frequency accurately in the channels assigned for industrial equipment by incorporating an automatic frequency control device into the generator. When this is done it is not necessary to provide shielding at the fundamental frequency, or for any harmonics that fall within the assigned ISM bands listed in Table 1. It may, however, be necessary to provide shielding for other harmonics, and for any parasitic oscillations that fall outside the ISM bands.

6.4.3 Improved Shielding and Tightening of Fasteners

In a great many cases, improved shielding, filtering, and bonding of the equipment are the only practical solution to a problem. The steps to be followed are similar to those discussed in previous sections of this recommended practice.

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Annex Symbols and Units

(Informative)

(The following appendix is not a part of IEEE Std 140-1990, IEEE Recommended Practice for Minimization of Interference from Radio-Frequency Heating Equipment, but is included for information only.)

The general symbols and units used are given in the following list. Where more specific or restrictive meanings are indicated by subscripts, etc., they are further defined after the equation in which they are used. In some cases a symbol definition is repeated where used, merely for convenience.

Symbols

C = Capacitance in farads.
d = Distance from transmitter to receiver, in meters.
D = Conductor diameter of dipole antenna, in meters.
E = Root-mean-square electric field strength of a radio wave, in volts per meter.
f = Frequency, in hertz.
g = Power gain of an antenna (over that of an ideal isotropic antenna) considering only its directivity but not its losses.
g_r = Power gain of an antenna (over that of an ideal isotropic antenna) considering both its directivity and its losses.
H = Root-mean-square magnetic field strength, in amperes per meter.
h = Height above ground of antenna center of radiation, in meters.
I = Root-mean-square antenna current, in amperes.
K = Calibration factor of a commercial field-strength meter.
l_p = Effective length of dipole antenna, in meters.
L_p = Physical length of a linear dipole antenna, in meters.
l_L = Effective length of loop antenna, in meters.
l_V = Effective length of grounded vertical antenna, in meters.
L_V = Physical length of grounded vertical antenna, in meters.
N = Number of turns.
P = Power, in watts.
Q = 2π times the ratio of energy stored to energy dissipated per cycle (Q is normally expressed as the ratio of inductive reactance to resistance at resonance).
R = Resistance, in ohms.
S = Mean area per turn of loop, in square meters.
V = Root-mean-square voltage, in volts.
α = Attenuator ratio (equal to, or greater than, unity).
λ = Wavelength, in meters.
ε_r= Relative dielectric constant of the ground, i.e., the ratio of permittivity (dielectric constant) of ground to that of vacuum.
σ= Ground conductivity, in mhos per meter.
c = Velocity of propagation of an electromagnetic wave in a vacuum ($2.997\,925 \pm 0.000\,003 \cdot 10^8$ m/s).
Z_o = Impedance of free space ($4\pi c \cdot 10^{-7} = 376.7304 \pm 0.0004\ \Omega$)

Unless otherwise stated, quantities are assumed to be those of the International System. For convenience, several relationships and prefixes are tabulated.

1 in = 0.0254 m

1 mi = 1609.344 m

1 m = 0.000 621 371 2 mi

1 in^2 = 0.000 645 16 m^2

1 m^2 = 1550.0031 in^2

pico	=	10^{-12}	deka	=	10
nano	=	10^{-9}	hecto	=	10^2
micro	=	10^{-6}	kilo	=	10^3
milli	=	10^{-3}	mega	=	10^6
centi	=	10^{-2}	giga	=	10^9
deci	=	10^{-1}	tera	=	10^{12}

Quantity	**Name of SI Unit**	**Number of CGS Electromagnetic Units in 1 SI Unit**
length	meter	100
area	square meter	10000
frequency	hertz	1
voltage	volt	10^8
electric field strength	volt per meter	10^6
current	ampere	1/10
power	watt	10^7
resistance	ohm	10^9
conductivity	mho per meter	10^{-11}
inductance	henry	10^9
capacitance	farad	10^{-9}
magnetic field strength	ampere per meter	$4\pi\cdot10^{-3}$